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(54) Abstract Title
Confocal microscopic equipment for measuring solid shapes

(57) Confocal Microscopic equipment for measuring the solid shape of a sample (13) without transverse scanning of a light beam, comprises a source (8) irradiating a light beam onto an aperture array (10), an objective lens (12) forming a stationary image of the apertures on the sample (13), a beam splitter (11) directing light from the apertures to the sample through the lens and directing reflected or fluorescent light from the sample to a photodetector (14). To determine the height of the surface the beam is scanned in the direction A and the light becomes maximum on the detector at the focal position. The light from the source may be S polarised and then directed to the sample through a polarised beam splitter and a quarter-wave plate which converts it to circularly polarised light. The quarter-wave plate converts the returning light into P polarised light so that it is deflected to the photodetector by the polarised beam splitter.

FIG. 3

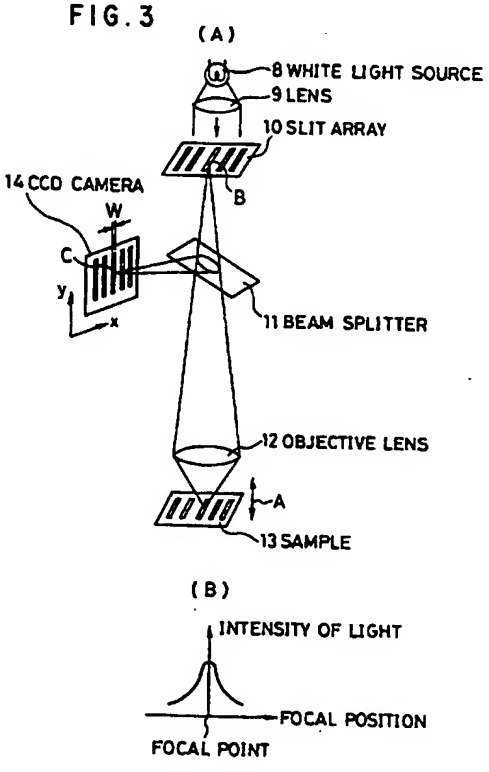

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FIG. 1

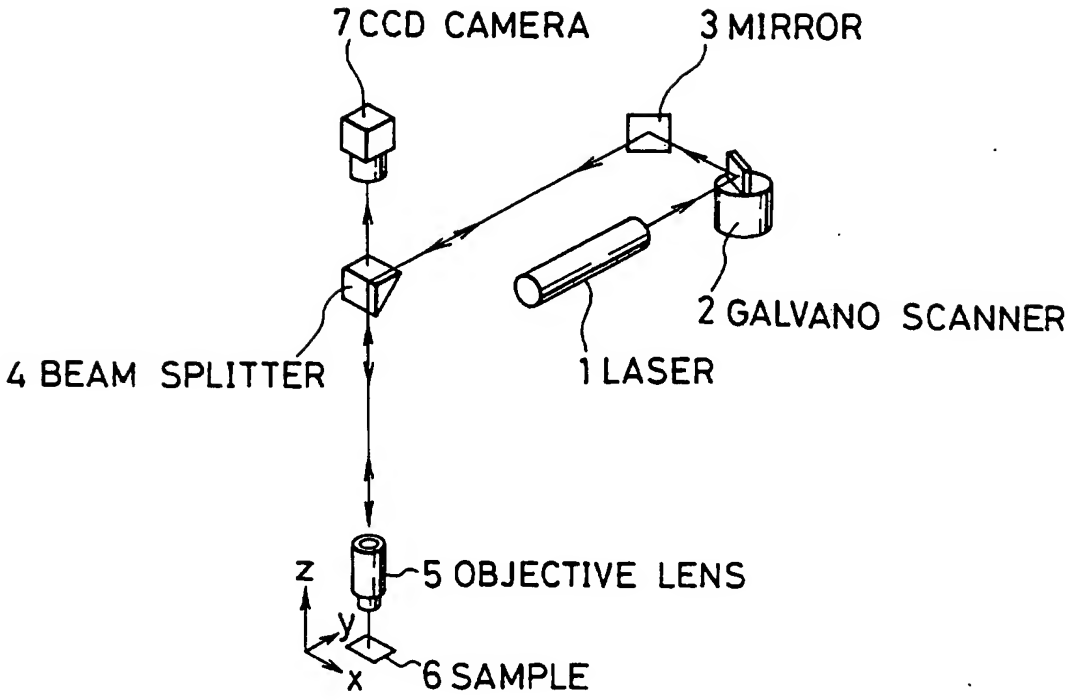

7 CCD CAMERA
3 MIRROR
2 GALVANO SCANNER
4 BEAM SPLITTER
1 LASER
5 OBJECTIVE LENS
z
y
x
6 SAMPLE

FIG. 2

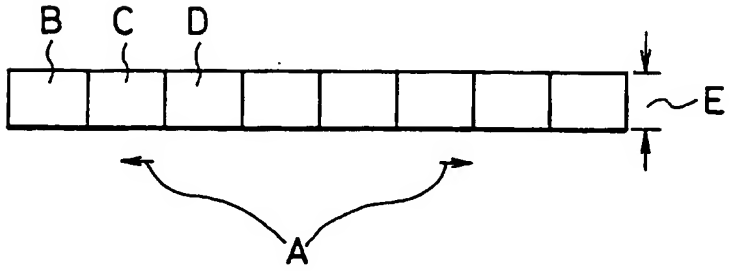

B
C
D
E
A

FIG. 3

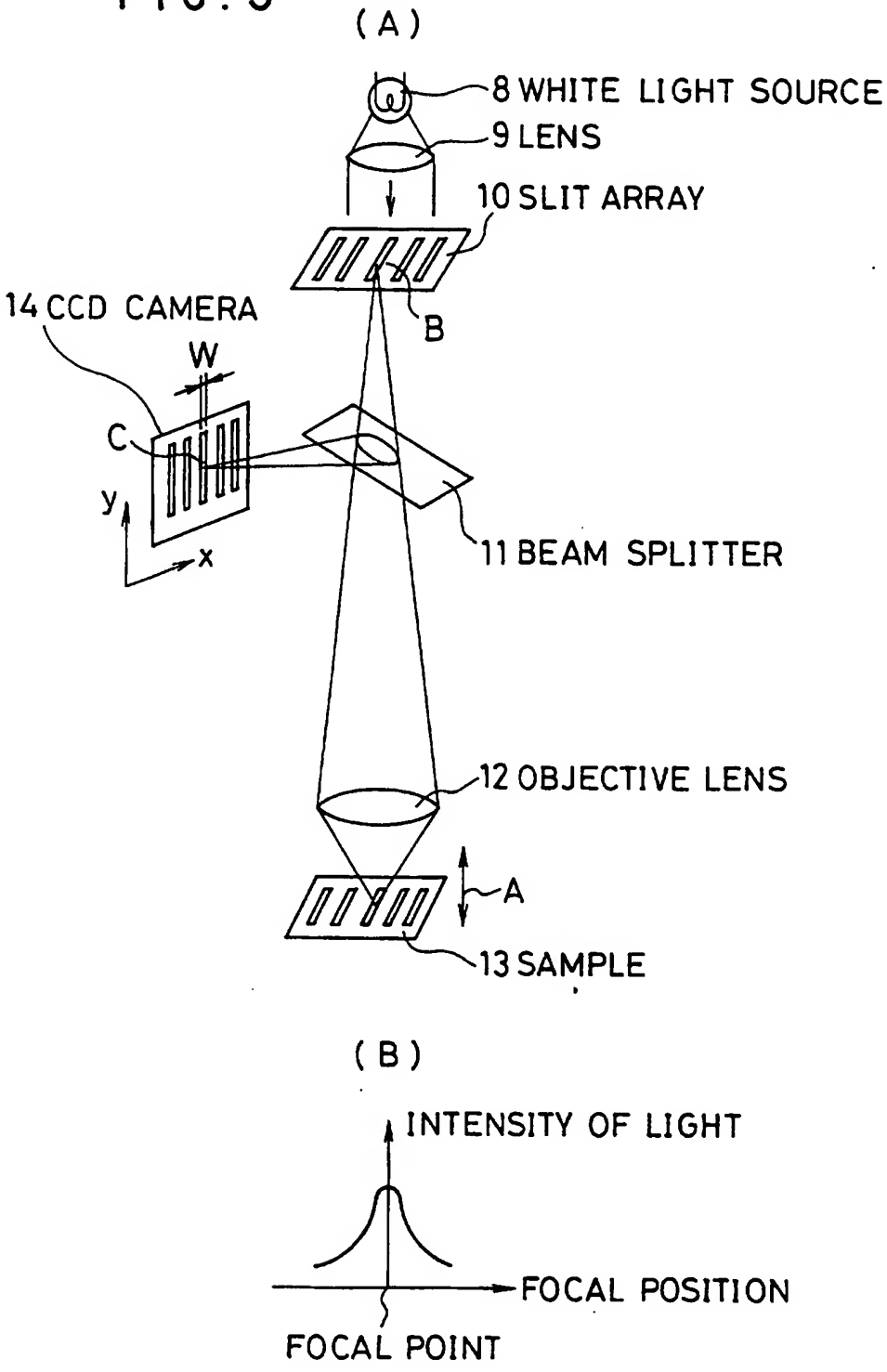

(A)
8 WHITE LIGHT SOURCE
9 LENS
10 SLIT ARRAY
B
14 CCD CAMERA
W
C
y
x
11 BEAM SPLITTER
12 OBJECTIVE LENS
A
13 SAMPLE
(B)
INTENSITY OF LIGHT
FOCAL POSITION
FOCAL POINT

FIG. 4

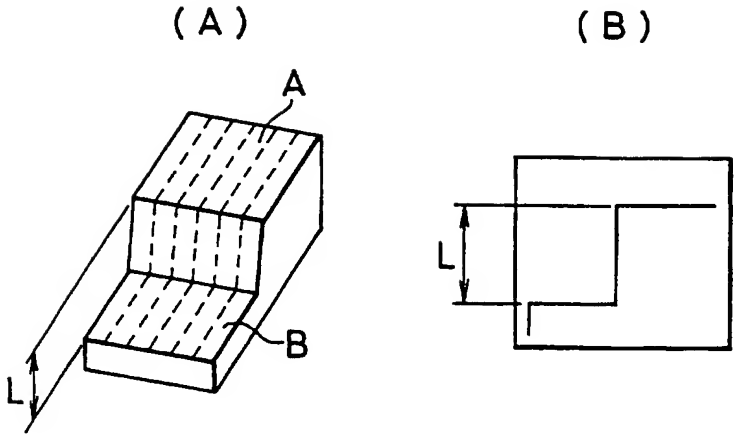


FIG. 5

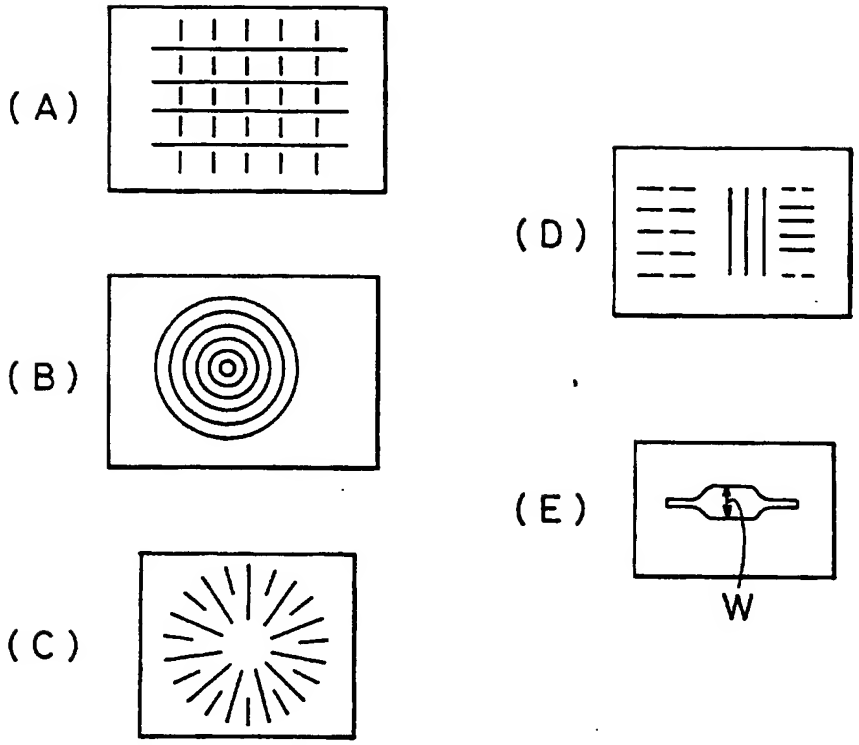


FIG. 6

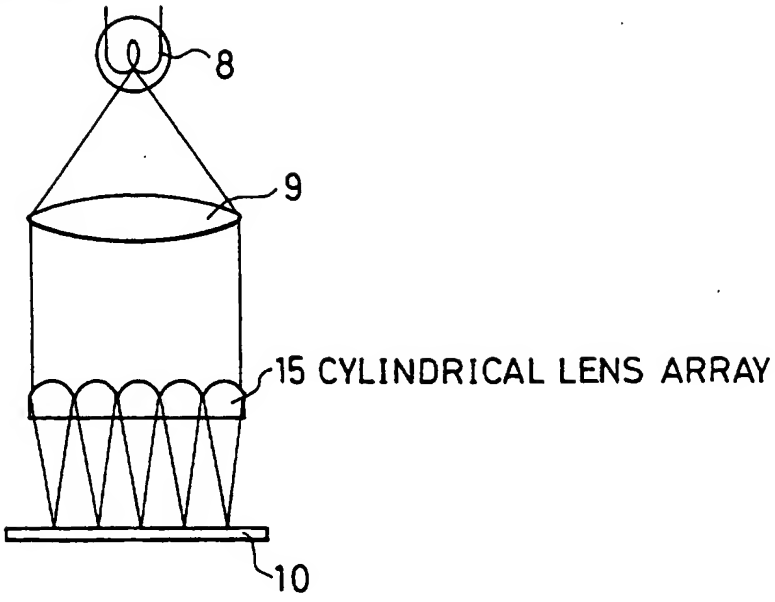

8
9
15 CYLINDRICAL LENS ARRAY
10

FIG. 7

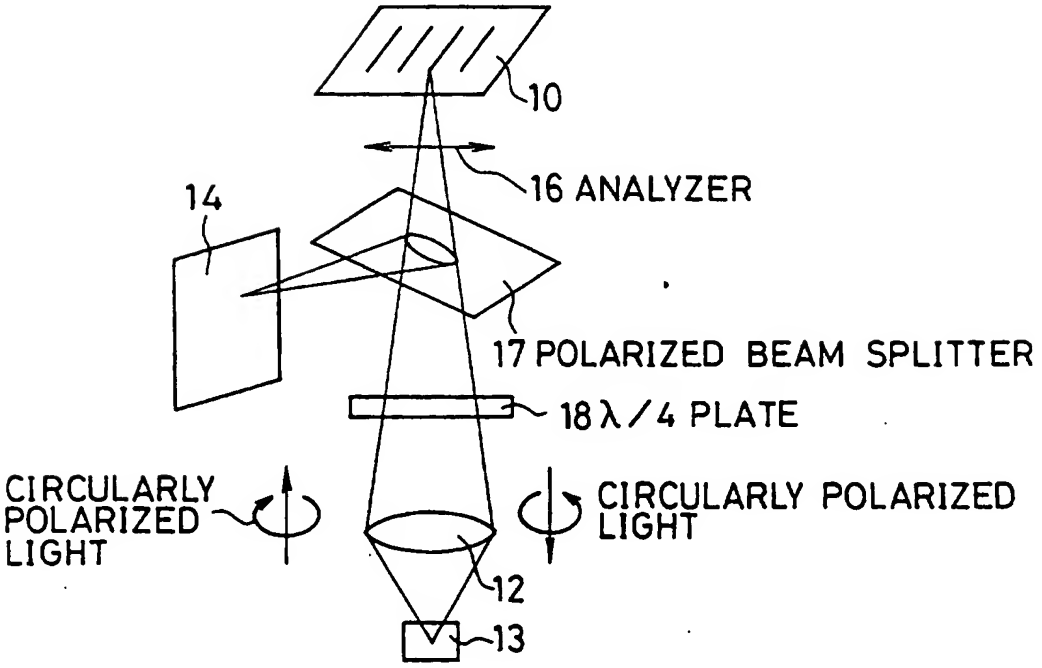

10
16 ANALYZER
14
17 POLARIZED BEAM SPLITTER
18 λ/4 PLATE
CIRCULARLY POLARIZED LIGHT
CIRCULARLY POLARIZED LIGHT
12
13

FIG. 8

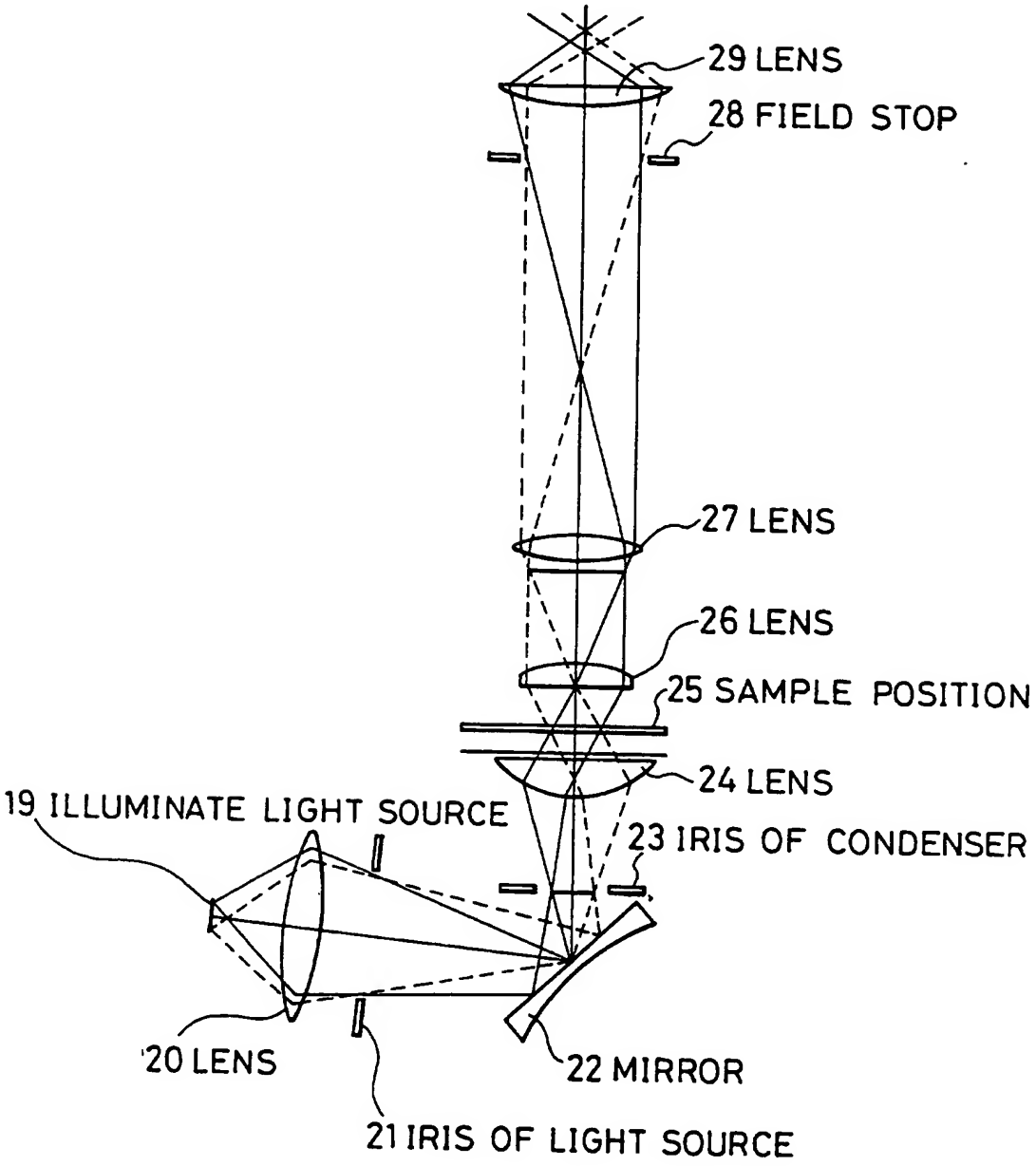

29 LENS
28 FIELD STOP
27 LENS
26 LENS
25 SAMPLE POSITION
24 LENS
19 ILLUMINATE LIGHT SOURCE
23 IRIS OF CONDENSER
20 LENS
22 MIRROR
21 IRIS OF LIGHT SOURCE

FIG. 9

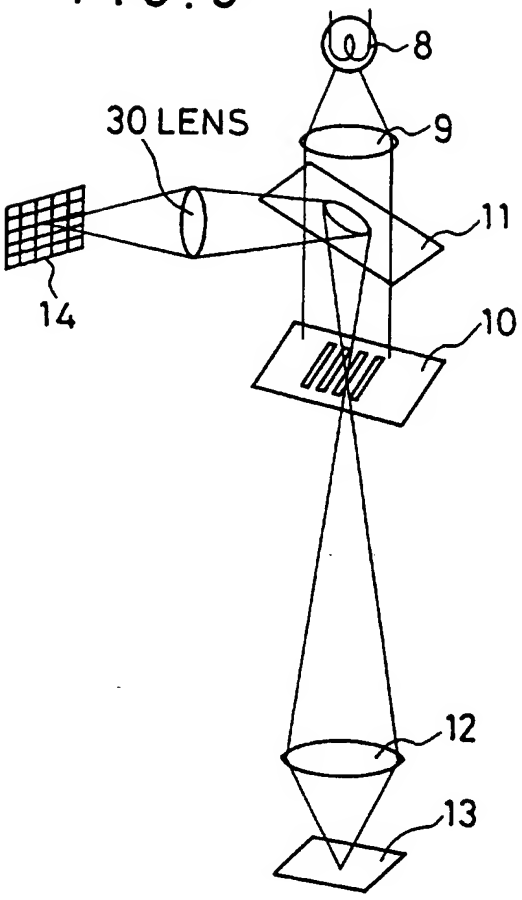
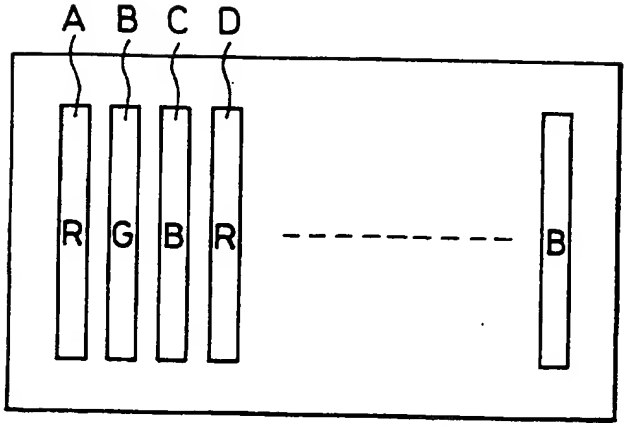


FIG. 10



CONFOCAL MICROSCOPIC EQUIPMENT

The present invention relates to confocal microscopic equipment that can measure the solid shape of a sample at high speed, and in particular, relates to equipment that does not require scanning of an irradiating beam using light.

Confocal miscroscopic equipment has resolution in the direction of the optical axis as well as resolution on a sample surface by scanning the irradiating beam on the above sample and detecting the light reflected from the sample through a pinhole or slit.

The resolution in the direction of the optical axis obtained by detecting the light through a slit is described in the following paper: "Three-dimensional optical-transfer-function analysis for a laser-scan fluorescence microscope with an extended detector," by S Kawata, R. Arimoto, and O. Nakamura, J. Opt. Soc. Am. A, Vol. 8, No. 1 (1991).

Figure 1 shows the configuration of an example of such conventional confocal microscopic equipment. The output light beam of laser 1 is incident to galvano-scanner 2 and then the reflected beam from galvano-scanner 2 is incident to beam-splitter 4 via mirror 3. Beam-splitter 4 reflects the incident beam from galvano-scanner 2 and makes the reflected light irradiate sample 6 via objective lens 5. The reflected light from sample 6 is again incident to objective lens 5 and then incident to one-dimensional charge coupled device (CCD) camera 7 via beam-splitter 4.

Hereafter, operation of the conventional equipment shown in Figure 1 will be described using Figure 2. The view shown in Figure 2 will be used to explain the details of each pixel of CCD camera 7.

The output beam of laser 1 is scanned by galvano-scanner 2 and this scans the irradiating beam on sample 6 in a one-dimensional direction. The reflected beam from sample 6 scanned in a one-dimensional direction is incident to CCD camera 7.

In CCD camera 7, the reflected beam scanning direction is set to match the direction marked "A" in Figure 2, and for example, the reflected beam is detected in turn with such pixels marked "B", "C", and "D" in Figure 2. In this case, since each pixel can detect the reflected beam only in the range of the height of pixel marked "E" in Figure 2, this means that pixels detect almost only the reflected beam that has passed a slit of width "E."

That is, if it is assumed that the direction of the optical axis is the z-axis, the plane orthogonal to the optical axis is the x-y plane and the direction of scanning is the x-axis, then the equipment has resolution also in the z-axis direction. Thus, the fault shape of the

x-z plane can be measured by scanning sample 6 in the z-axis direction. In addition, measurement of the solid shape of the entire sample 6 is made possible by scanning sample 6 in the z-axis direction while moving sample 6 in the y-axis direction in turn.

As a result, the resolution in the direction of the optical axis as well as the resolution on the above sample surface can be obtained by scanning a laser beam in a one-dimensional direction and detecting the reflected light with one-dimensional line CCD camera 7.

However, there are problems in conventional equipment such as shown in the example of Figure 1 that expensive optical equipment such as laser 1 is necessary and a scanning means such as galvano-scanner 2 is required.

In addition, there are the following problems also in the conventional equipment: the wavelength becomes longer and the resolution worsens because the laser to be incorporated in the confocal microscopic equipment can use only the red color system due to size and price. Further, since the laser beam is a coherent light beam, speckle noise is generated that degrades the S/N ratio.

According to the invention, there is provided confocal microscopic equipment for measuring solid shapes of samples, comprising:

a light source,

apertures on which the output beam of this light source is irradiated,

an objective lens which forms stationary images of the said apertures on the said sample and focuses the reflected beam or fluorescence from the said sample,

a photo-detector, and

a beam-splitter that transmits or reflects the beam passing the said apertures and makes it incident on the said objective lens, and makes the output beam from the said objective lens incident on the said photo- detector by means of reflection or transmission.

The invention will now be described in greater detail, by way of example, with reference to the drawings, in which:-

Figure 1 shows the configuration of an example of conventional confocal microscopic equipment;

Figure 2 is a plane view used to describe the details of each pixel of the CCD camera;

Figure 3 shows the configuration for an embodiment of confocal microscopic equipment of the present invention;

Figure 4 includes a perspective view of a sample having a three-dimensional shape and the image of a cross-sectional view of the sample;

Figure 5 shows example views of aperture shapes;

Figure 6 indicates the configuration for an embodiment of the present invention using a cylindrical lens array;

Figure 7 indicates the configuration for an embodiment of the present invention using a polarized beam-splitter;

Figure 8 indicates the configuration for an embodiment of the present invention using a illuminating system of microscopes;

Figure 9 shows the configuration for another embodiment of confocal microscopic equipment of the present invention, and

Figure 10 is a plane view showing slits to which color filters are attached.

Hereinafter, the present invention will be described in detail using drawings.

Figure 3 shows the configuration for an embodiment of confocal microscopic equipment of the present invention. The output beam of white light source 8, which is an incoherent light source, is incident to slit-array 10 in which a plurality of slits, or apertures, are provided (hereinafter abbreviated as "slit-array") through lens 9. The beams that pass each slit of slit-array 10 are incident to beam-splitter 11, such as a half mirror dichroic mirror. Beams that are transmitted through beam-splitter 11 irradiate sample 13 through objective lens 12.

The reflected beam from sample 13 is again incident to beam-splitter 11 through objective lens 12 and the beam reflected by beam-splitter 11 is incident to two-dimensional CCD camera 14 which is a photo-detector. Further, sample 13 is scanned in the direction of the optical axis marked "A" in Figure 3 by a means not shown in the figure.

Here, operation of the embodiment shown in Figure 3 (A) is described using Figure 3 (B). Slit-array 10 is placed on the image-forming plane of objective lens 12 and the slit width is the same as that of the Airy first dark band on the above image-forming plane. The distance between slits is about 10 times the above slit width.

If light is collected with a lens, actually it is not focused into a point neatly but forms a fine image in which light and dark rings are arranged alternately surrounding the center light part. These rings are called "Airy disks" and the dark ring adjacent to the center part is the above Airy first dark band.

Let the width of the Airy first dark band be "b," wavelength be "λ" and the numerical aperture be "NA," then

$$b = 1.22 \times \lambda/NA \quad (1)$$

For example, if it is assumed that the magnification of objective lens 12 is 100, the numerical apertures NA of objective lens 12 = 0.9 and λ = 0.5 μm, then since the numerical apertures in the place of "B" in Figure 3 (A) becomes 1/100,

$$B = 1.22 \times 0.5/(0.9/100)$$
$$= 68\mu m \quad (2)$$

Therefore, a slit having the width like this can be easily prepared by etching or other methods.

When the output beam of white light source 8 is incident to slit-array 10, a plurality of slit images of slit-array 10 are formed on sample 13 by means of objective lens 12. The slit images on sample 13 are incident to CCD camera 14. CCD camera 14 is a two-dimensional CCD camera and multiple pixels are arranged on a plane. By considering the pixel array corresponding to the slit width, the camera detects only the reflected light passing through a slit of fixed width as described before.

For example, the slit image marked "C" in Figure 3 (A) is measured by the pixel array in the place where the image is formed. If the width of pixel array in the x-direction in Figure 3 (A) is assumed to be "W," the above pixel array detects only the beam passing through the slit whose width is "W." Therefore, such equipment has resolution in the direction of the optical axis as well as resolution on the above sample surface.

In this case, if the surface 13 is located at the focal plane of objective lens 12, the slit images are clear but if sample 13 is moved upward or downward from the above focal plane by a means not shown in the figure, the above slit images become out of focus.

If such slit images are detected by pixels of width "W" on CCD camera 14, a maximum intensity of light is incident in the case where the focal position coincides with

the focal plane as shown in figure 3 (B). The incident intensity of light decreases as the focal position shifts from the focal plane.

In other words, the focal position in which the incident intensity of light becomes the maximum shows the height of the sample in the direction of the optical axis.

Accordingly, a change of the surface of sample 13 in the direction of the optical axis can be obtained by the following. That is, the focal position in which the intensity of light measured by CCD camera 14 becomes the maximum is determined by scanning sample 13 in the direction of the optical axis marked "A" in Figure 3 with a means not shown in the figure.

For instance, if a sample of three-dimensional shape having a step "L" as shown in Figure 4 is measured by confocal microscopic equipment proposed by the present invention, slit images are formed as shown with broken lines in Figure 4 (A).

If the plane of "A" in Figure 4 (A) is the focal plane, the slit image of plane "B" in Figure 4 (A) becomes out of focus. Conversely, if the plane of "B" in Figure 4 (A) is the focal plane, the slit image of plane "A" in Figure 4 (A) becomes out of focus.

Thus, a fault (tomographic) image as shown in Figure 4 (B) can be produced by determining focal positions in which the maximum intensity of light is input to each pixel of CCD camera 14 respectively.

As a result, the resolution in the direction of the optical axis is obtained without scanning an irradiating beam using incoherent light. That is, this can be achieved by forming slit images on the sample surface and determining respectively focal positions in which the maximum intensity of light is input to each pixel of CCD camera 14 which is a photo-detector.

In addition, the equipment of the present invention has resolution in the direction of the optical axis as well as resolution equivalent to that of an ordinary optical microscope in the direction orthogonal to the optical axis.

As for the objective lens 12, it may focus fluorescence from sample 13 not limited to the reflected beam from sample 13.

In the embodiment shown in Figure 3, the transmitted beam through beam-splitter 11 is focused on sample 13 and the reflected beam from beam-splitter 11 is incident to CCD camera 14. However, the configuration, in which the reflected beam from beam-

splitter 11 is focused on sample 13 and the transmitted beam through beam-splitter 11 is incident to CCD camera 14, may be taken as well.

In addition, if the slit width is increased, the intensity of light increases but spatial resolution decreases, while if the slit width is decreased, the spatial resolution is improved but the intensity of light decreases. Hence, the slit width need not be limited to the width of the Airy first dark band but it is sufficient for the width to be from approximately 1/20 up to twenty times the diameter of the Airy first (circular) dark band.

Similarly, if the pitch of the slits is increased, the resolution in the direction of the optical axis is improved because interference by adjacent slits is reduced but the number of slits that can be simultaneously measured decreases. While, if the above distances are made smaller, the number of slits increases but interference between slits is generated, which makes correct measurement difficult.

Therefore, the pitch of the slits is not limited to ten times the Airy first dark band width but it is sufficient for the distance to be about twice or more the Airy first dark band width.

Further, the photo-detector is not limited to a CCD camera but a camera tube, film or the like may be used, and direct observation by the human eye using an ocular can also be adopted.

The shape of apertures is not limited to slits but a reticulate aperture as shown in Figure 5(A) by arranging multiple slits orthogonal to each other may be used. Such an aperture shape can measure the three-dimensional shape of a sample more accurately.

In addition, if a sample has a spherical shape, the use of multiple rings or radial slits as shown in Figure 5 (B) or (C) is effective. If the shape of a sample is known in advance, an aperture shape such as that shown in Figure 5 (D) for which the place requiring measurement is limited is also effective. If the reflectivity of the sample surface varies depending on the location on it, the width of the slit "W" corresponding to places of small reflectivity may be wider as shown in Figure 5 (E).

If the apertures consist of pinholes of diameter approximately the same as that of the Airy first dark band, coherent light can be employed because speckle noise is not generated even if coherent light is used. As the apertures, not only an etched metal plate but also a light-shielding film formed on a glass substrate partially removed by etching may be used.

It is also possible to compose the apertures using a transmitting liquid crystal panel. In this case, such apertures are effective because the shape or the like of apertures can be electrically and conveniently changed.

If the shapes between slits are to be measured, images between slits can be interpolated by moving slits in the direction orthogonal to the optical axis, obtaining multiple solid images, and composing them thereafter. In this case, a stage or the like on which a sample or slits are provided may be moved, or the above measurement can be realised by moving apertures, changing the shape, etc. by controlling the above described transmitting liquid crystal panel.

In the embodiment shown in Figure 3, the ratio of slit width to slit interval is 1:10. This indicates that the ratio of aperture areas is 10% and only 10% of the incident beam is utilized. For this reason, a configuration as shown in Figure 6 may be taken.

The output beam of white light source 8 is incident to cylindrical lens array 15 which is a focusing means through lens 9 and the beam converged by cylindrical lens array 15 is incident to each slit of slit array 10. Each slit of slit array 10 is placed at each focal point of cylindrical lenses respectively.

By employing the configuration shown in Figure 6, the incident beam can be effectively utilized. In addition, as the focusing means, not only ordinary convex lenses by also Fresnel lenses and refractive index-distributed lenses can be used. Further, if a transmitting liquid crystal panel is used for apertures, micro-lenses may be added to each liquid crystal element.

For beam-splitter 11, a half mirror has been shown as an example but a polarized beam-splitter can also be used. Figure 7 shows, the configuration indicating an embodiment of the present invention using a polarized beam-splitter.

For example, polarizer 16 coverts the transmitted beam to S polarized light. Polarized beam-splitter 17 transmits S polarized light and reflects P polarized light. The light passing slit array 10 becomes S polarized light by being transmitted through polarizer 16 and is incident to polarized beam-splitter 17. This S polarized light is incident to quarter-wave ($\lambda/4$) plate 18 after transmitting through beam-splitter 17. The incident light thus becomes circularly polarized light, which irradiates sample 13 through objective lens 12. The reflected light from sample 13 is again incident to quarter-wave plate 18 through objective lens 12. As a result, the circularly polarized light returns to linearly polarized

light and is incident to polarized beam-splitter 17 as 90-degree rotated P polarized light. So, the P polarized light is reflected by polarized beam-splitter 17 and is incident to CCD camera 14.

As a result, 100% of the incident light from slit array 10 can be incident to the CCD camera, compared with the case where a half mirror is used.

As a means which scans sample 13 in the direction of the optical axis, the method of moving the stage of the microscope by pulse motors or the like is generally adopted. However, sample 13 or slit array 10 may also be moved using piezo-electric elements. In addition, objective lens 12 itself may be moved in the direction of the optical axis.

Although slit array 10 is mounted on the image-forming plane of objective leans 12 in the embodiment shown in Figure 3, an illuminating system for microscopes can also be employed.

Figure 8 indicates the configuration for an embodiment of the present invention using an illuminating system of microscopes. The output beam of illuminating light source 19 is focused with lens 20 and is incident to mirror 22 through iris of light source 21. This incident beam is reflected by mirror 22 and is then incident to lens 24 through iris of condenser 23. Transmitted light through lens 24 illuminates sample position 25 and is finally incident to lens 29 through lenses 26 and 27 and field stop 28 respectively and then observed.

Hereafter, operation of the embodiment shown in Figure 8 will be described. Since an image located in the position of iris of light source 21 is formed on sample position 25, the apertures, such as slit array 10, are provided in the position of the iris of light source. Since the image of the apertures, such as slit array 10, is projected on sample position 25 in this way, observation of this image using an ordinary ocular or camera makes it possible to easily change an ordinary microscope into a confocal system. Although Figure 8 illustrates a microscope having an illuminating system of transmitted-light illumination, this concept is also applicable to the illuminating system of reflected illumination.

In Figures 3 and 7, the system has the configuration in which the beam transmitted through slit array 10 is incident to beam-splitter 11 or polarized beam-splitter 17. However, it may have the configuration shown in Figure 9. The difference of configuration in Figure 9 from that of Figure 3 is that beam-splitter 11 is located between

light source 8 and slit array 10. In addition, lens 30 becomes necessary in Figure 9 to focus the branched light on CCD camera 14.

As described above, if shapes between slits are to be measured, images between slits are interpolated by composing cross-sectional images obtained by moving slits in the direction orthogonal to the optical axis. This is because the distances between slits are made about twice the width of the Airy first dark band or more to suppress interference between adjacent slits. However, the following method can also be used for this purpose.

That is, as shown in figure 10, slits to which different color filters are attached are located close to each other and the same color filters as relevant slits are also arranged on the CCD camera located on the photo-detecting side.

For example, in Figure 10, red filters are attached to the slits marked "A" and "D," a green filter to the slit marked "B," and a blue filter to the slit marked "C."

Interpolation between slits becomes possible by performing data processing for each filter color on the cross-sectional images obtained in such configuration, and thus, spatial resolution is improved three-fold.

In addition, filter colors are not limited to the above three colors but a similar effect can also be obtained by employing color liquid crystals as color filters and using a color CCD camera.

The application of the equipment of the present invention is not limited to microscopes but the shapes of large-size objects, such as mechanical parts, can also be measured by using an ordinary camera lens in place of the objective lens.

The confocal microscopic equipment that does not require scanning of an irradiating beam can be realised by adopting the configuration described in the present invention. That is, in this configuration, slit images are formed on the sample surface and the focal positions in which the maximum intensity of light is input to each pixel of the CCD camera, a photo-detector, are determined respectively.

Further, the use of incoherent light as the irradiating beam improves the resolution because spectral light components of shorter wavelengths, such as blue color or ultra-violet light, can be utilized, and this does not generate speckle noise.

CLAIMS:

1. Confocal microscopic equipment for measuring solid shapes of samples, comprising:

a light source,

apertures on which the output beam of this light source is irradiated, an objective lens which forms stationary images of the said apertures on the said sample and focuses the reflected beam or fluorescence from the said sample,

a photo-detector, and

a beam-splitter that transmits or reflects the beam passing the said apertures and makes it incident on the said objective lens, and makes the output beam from the said objective lens incident on the said photo-detector by means of reflection or transmission.

2. Confocal microscopic equipment in accordance with claim 1, wherein the said beam-splitter is located midway between the said light source and the said apertures.

3. Confocal microscopic equipment in accordance with claim 1 or claim 2, wherein the said apertures have the shapes including circular or rectangular shapes, reticulate shapes by arranging multiple orthogonal slits, multiple-ring shapes or radial slit shapes.

4. Confocal microscopic equipment in accordance with claim 1 or claim 2, wherein the widths of the said apertures are from 1/20 up to twenty times the diameter of the Airy first dark band.

5. Confocal microscopic equipment in accordance with claim 4, wherein the light source is an incoherent light source.

6. Confocal microscopic equipment in accordance with claim 1 or claim 2, wherein the said apertures are formed by etching the light-shielding film formed on a metal plate or a glass substrate.

7. Confocal microscopic equipment in accordance with claim 1 or claim 2, wherein the said apertures consist of transmitting liquid crystal panels.

8. Confocal microscopic equipment in accordance with claim 1 or claim 2, wherein the said plurality of apertures are arranged at the distances of twice or more the width of the Airy first dark band.

9. Confocal microscopic equipment in accordance with claim 8, wherein the images between the said plurality of adjacent apertures are interpolated by composing a plurality of cross-sectional images obtained by moving the said plurality of apertures in the direction orthogonal to the optical axis.

10. Confocal microscopic equipment in accordance with claim 1 or claim 2, wherein different color filters are attached to the said plurality of apertures and the said plurality of apertures are located close to each other.

11. Confocal microscopic equipment in accordance with claim 1 or claim 2, wherein the said confocal microscopic equipment is provided with a focusing means that is located between the said light source and the said apertures and focuses the output beam of the said light source on the said apertures.

12. Confocal microscopic equipment characterized by providing the said apertures in the place of the iris of the light source for reflected illumination, fluorescence illumination or transmitted-light illumination.

13. Confocal microscopic equipment for measuring the solid shapes of samples, comprising:

a light source,

a polarizer that converts the output light of the said light source to linearly polarized light,

apertures on which the output beam of the said polarizer is irradiated, an objective lens that forms the images of the said apertures on the said sample and focuses the reflected beam from the said sample,

a photo-detector,

a polarized beam-splitter that makes the beam passing the said apertures incident to the said objective lens by means of transmission or reflection and that focuses the output beam from the said objective lens focus onto the said photo-detector by means of reflection or transmission, and

a quarter-wave plate provided between the said objective lens and the said polarized beam-splitter.

14. Confocal microscopic equipment in accordance with claim 13, wherein the said polarized beam-splitter is located midway between the said light source and the said apertures.

15. Confocal microscopic equipment for measuring the solid shapes of samples substantially as described herein with reference to figures 3 to 10 of the drawings.

The Patent Office

Application No:	GB 9800966.5	**Examiner:**	Bob Clark
Claims searched:	All	**Date of search:**	30 April 1998

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): G1A (AEXP, AEY); H4D (DLAU, DLAV, DLRG)

Int Cl (Ed.6): G01B 11/00, 11/24, 11/30; G02B 21/00

Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	US 5239178	(DERDINGER et al.) Whole document	1-9,11,12
X	US 5248876	(KERSTENS et al.) Particularly line 2 column 4 to line 16 column 6, and line 13 column 11 to line 64 column 12.	1-6, 8-14

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.